Int J Life Cycle Assess (2014) 19:1593–1606
DOI 10.1007/s11367-014-0773-7

CARBON FOOTPRINTING

Greenhouse gas emissions from forestry in East Norway

Volkmar Timmermann · Janka Dibdiakova

Received: 17 December 2013 / Accepted: 22 June 2014 / Published online: 11 July 2014

Abstract

Purpose So far no calculations have been made for greenhouse gas (GHG) emissions from forestry in East Norway. This region stands for 80 % of the Norwegian timber production. The aim of this study was to assess the annual GHG emissions of Norwegian forestry in the eastern parts of the country from seed production to final felling and transport of timber to sawmill and wood processing industry (cradle-to-gate inventory), based on specific Norwegian data.

Methods The life cycle inventory was conducted with SimaPro applying primary and secondary data from Norwegian forestry. GHG emissions of fossil-related inputs from the technosphere were calculated for the functional unit of 1 m^3 timber extracted and delivered to industry gate in East Norway in 2010. The analysis includes seed and seedling production, silvicultural operations, forest road construction and upgrading, thinning, final felling, timber forwarding and timber transport on road and rail from the forest to the industry. Norwegian time studies of forestry machines and operations were used to calculate efficiency, fuel consumption and transport distances. Due to the lack of specific Norwegian data in Ecoinvent, we designed and constructed unit processes based on primary and secondary data from forestry in East Norway.

Results and discussion GHG emissions from forestry in East Norway amounted to 17.893 kg CO_2-equivalents per m^3 of timber delivered to industry gate in 2010. Road transport of timber accounted for almost half of the total GHG emissions, final felling and forwarding for nearly one third of the GHG emissions. Due to longer road transport distances, pulpwood had higher impact on the climate change category than saw timber. The construction of forest roads had the highest impact on the natural land transformation category. The net CO_2 emissions of fossil CO_2 corresponded to 2.3 % of the CO_2 sequestered by 1 m^3 of growing forest trees and were compared to a calculation of biogenic CO_2 release from the forest floor as a direct consequence of harvesting.

Conclusions Shorter forwarding and road transport distances, increased logging truck size and higher proportion of railway transport may result in lower emissions per volume of transported timber. A life cycle assessment of forestry may also consider impacts on environmental categories other than climate change. Biogenic CO_2 emissions from the soil may be up to 10 times higher than the fossil-related emissions, at least in a short-term perspective, and are highly dependent on stand rotation length.

Keywords Carbon footprint · Greenhouse gas emissions · LCA · LCI · Norwegian forestry · Timber transport

1 Introduction

Life cycle inventory (LCI), which is the data collection part of life cycle assessment (LCA), is a functional accounting of environmental impacts throughout the whole life cycle of a product or service, from resource extraction and production to use phase and final disposal, including all processes involved in the system of interest. The LCI tool allows a systematic comparison of different processes within a life cycle and of alternative system configurations. It allows detailed tracking of all the flows in and out of the product system, including raw resources or materials, energy by type, water and emissions to air, water and land by specific substances (Jungmeier et al. 2003). This kind of analysis can be complex and may involve hundreds of individual unit processes in a supply chain. LCA is a multi-step procedure for calculating the lifetime

Responsible editor: Göran Finnveden

V. Timmermann (✉) · J. Dibdiakova
Norwegian Forest and Landscape Institute, P.O. Box 115, 1431 Ås, Norway
e-mail: volkmar.timmermann@skogoglandskap.no

environmental impact of a product or service (Solli et al. 2009; Ximenes and Grant 2013). There are two major approaches for performing LCA. The attributional LCA evaluates the impacts of all processes involved in the life cycle of a product, including relevant flows into and out of the system. In contrast to attributional LCA, consequential LCA is a conceptually wider approach considering how production would be affected by different decisions made outside the system (Brander et al. 2009; Finnveden et al. 2009). Both forms of LCA, however, can yield valuable insights about potential environmental effects.

Nearly all human activities lead to greenhouse gas (GHG) emissions, either directly or indirectly. The most important GHG produced by human activities is carbon dioxide (CO_2). Direct GHG emission sources are often easy to identify, for example, burning fossil fuels for electricity generation, heating and transport. It is sometimes less obvious that products and services also cause indirect emissions throughout their life cycles. Energy is required for production and transport of products, and GHGs are also released when products are disposed of at the end of their useful lives (Abbott 2008).

Forests and the value of forest land have been given more focus in recent years as a result of the discussions regarding climate change and the understanding of forests as an important factor in mitigating climate change. One important approach to achieve this understanding has been LCA. A wide range of forest products and industries have been examined by this tool in order to estimate the impacts of a product or activity on the amount of atmospheric GHGs (Jungmeier et al. 2003; Gustavsson and Sathre 2006; Salazar and Sowlati 2008; Heath et al. 2010; Parigiani et al. 2011). The use of forests and forestry operations is a two-way street, meaning that forestry can affect CO_2 emissions either by increasing or decreasing carbon stocks in biomass, soil and products, or by supplying biofuels to replace fossil fuels. Establishing new forests can increase carbon storage, and growing trees have an important value in relation to emissions from forestry operations (Parigiani et al. 2011). Studies on forest management have shown that the rotation length, fertilization regime and intensity of site preparation and harvesting may have a positive effect on the above-ground carbon stock (Liski et al. 2001; Eriksson et al. 2007), while the same management practices might have a negative impact on the below-ground carbon stock (de Wit and Kvindesland 1999; Nave et al. 2010).

About 40 % of the Norwegian main land is covered by forest (Granhus et al. 2012). The total forested area in Norway amounts to almost 11 million hectares (ha), of which more than 8 million ha are productive forest (Granhus et al. 2012). Approximately 15 % of the productive forest has been estimated as non-profitable areas due to difficult terrain and remoteness, which means that cost-effective forestry may only be performed in circa 60 % of the forested area (Eid et al. 2002). An increase in forest productivity could be achieved through tree planting improvements and intensified forest management including e.g. increased fertilization and shorter rotations (Berg and Lindholm 2005; Trømborg 2011). Timber from Norwegian forests is important first and foremost as a source of raw materials for sawmill and pulp and paper industries. In the period from 2000 to 2009, the amount of harvested timber for industrial purposes has been considerably lower than the increment (Granhus et al. 2012).

There are various studies assessing contributions to the total GHG emissions of selected parts of timber product pathways (Berg and Karjalainen 2003; Berg and Lindholm 2005; Matthews et al. 2007; Lindholm 2010; Whittaker et al. 2011). Those studies all combine the knowledge of forest growth and carbon cycles, the relevant details of forest and timber operations, and the practical application of LCA. Several previous studies aimed at evaluating Norwegian forestry's contribution to GHG emissions. Michelsen et al. (2008) concentrated on forestry in the northern parts of Norway, while the study by Flæte (2009) was a calculation of GHG emissions from forestry based on fuel and energy use only on a national level. Considering that the forest area in East Norway stands for 80 % of the Norwegian timber production (SLF 2012), the present study had specific focus on this region. The aim of this work was to assess the annual GHG emissions of Norwegian forestry in the eastern parts of the country, on a 100-year life cycle horizon, from seed production to final felling and transport of timber to industry (cradle-to-gate inventory), based on specific Norwegian data. The present study was part of the project KlimaTre (ClimateWood), documenting the impact of Norwegian forestry value chains on climate and value added. A report from KlimaTre (Vennesland et al. 2013) containing raw data from recent time studies of forestry operations made it possible to conduct a detailed LCI on Norwegian forestry based on primary data specific for conditions in East Norway.

2 Methods

The reference functional unit (FU) used for the inventory analysis and impact assessment of the present work was 1 m^3 of timber under bark harvested in East Norway and delivered to industry gate in 2010. The system considered for this study and its boundary is illustrated by the model in Fig. 1. The analysis starts with seed and seedling production, followed by silviculture (including site preparation, reforestation, tending, spraying, fertilization and pruning), forest road construction and upgrading, thinning, final felling and other practices of harvesting, timber forwarding and timber

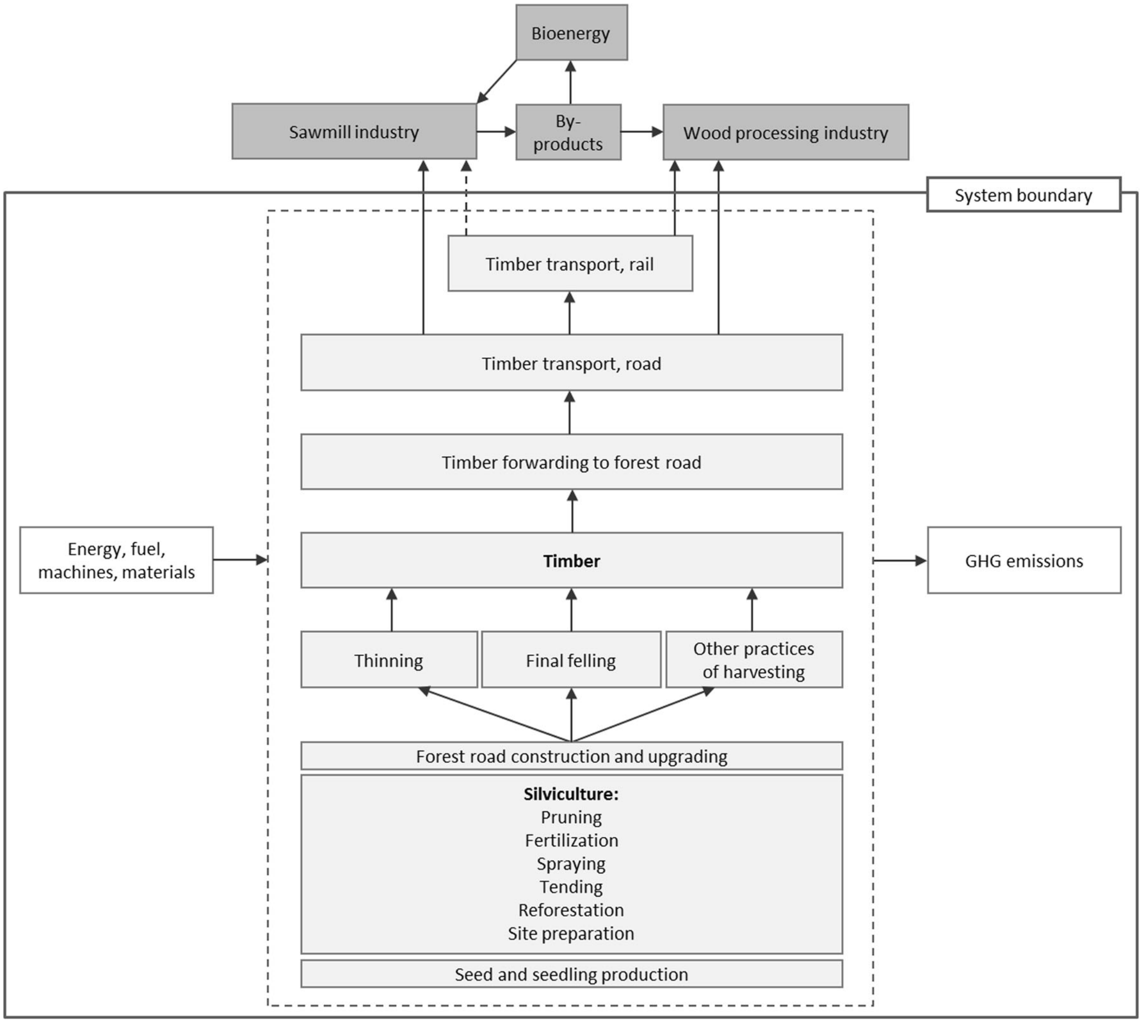

Fig. 1 Model of processes included and system boundary for the cradle-to-gate inventory

transport on road and rail from the forest to the sawmill and wood processing industry.

2.1 Software

The LCI was conducted with the SimaPro 7.3.3 software (SimaPro 2008) using the library Ecoinvent 2.2 (Ecoinvent 2007), with data adapted to European conditions. The ReCiPe midpoint impact methodology using the *hierarchic* (H) perspective was chosen. ReCiPe midpoint (H) impact methodology is a damage-oriented approach, based on the weight given to damages by the different impact categories (Goedkoop et al. 2009). It balances short- and long-term horizons and has a consensus-based approach to risk (Fantozzi and Buratti 2010). The ReCiPe midpoint (H) impact methodology uses a time horizon of 100 years for Global Warming Potential (GWP), which gives GWP equivalency factors of 298 for nitrous oxide (N_2O) and 25 for methane (CH_4), used for calculating CO_2-equivalents. However, it is acknowledged that other environmental impacts may be realized after a longer time horizon than 100 years (Hauschild et al. 2008; Holtsmark 2013; Ximenes and Grant 2013). A sensitivity analysis was conducted in SimaPro using Monte Carlo simulations (1000 runs), randomly drawing parameters employing a mixture of predefined distributions which is dominated by the lognormal distribution, based on uncertainties from Ecoinvent, where available. Mean values and standard deviations were calculated for the ensemble. We present the mean instead of the more conventional median, but carefully checked that the deviation of the two was minor.

2.2 Assessment assumptions and data sources

The region this study focused on consists of eight counties in East Norway, namely Østfold, Akershus, Oslo, Hedmark, Oppland, Buskerud, Vestfold and Telemark (Fig. 2). Conifers dominate in this region covering 75 % of the total forested area. About 53 % of the total standing volume in East Norway consists of Norway spruce (*Picea abies* (L.) Karst.) and 32 % of Scots pine (*Pinus silvestris* L.). Birches (*Betula* spp.) are the

Fig. 2 Location of the analysed region in East Norway (*dark-shaded area*)

most common of the deciduous species, making up 11 % of the standing volume, while other deciduous species only account for 4 % (Granhus et al. 2012). The length of a stand rotation in East Norway is about 60–120 years for spruce, 80–140 years for pine and about 40–60 years for birch, depending on the site index (Fitje 1989). In 2010, the total volume of extracted timber in Norway was 8.40 million m^3, and 6.68 million m^3 (80 %) of this volume was harvested in East Norway (SLF 2012). Spruce timber accounted for 76 %, pine timber for 23 % and birch timber for 1 %, respectively, of the total timber volume felled in this region in 2010 (SLF 2012). The proportion of saw timber was 52 % and that of pulpwood 48 % (SLF 2012). A forestry survey conducted in 2008 indicated that 83 % of the timber was coming from final felling, 15 % from thinning and 2 % from other practices of harvesting (SSB 2009). According to Vennesland et al. (2013), the average timber yield in 2010 was 50 m^3/ha from thinning and 230 m^3/ha from final felling. The average raw density of freshly cut round wood under bark was 765 kg per m^3 (Ecoinvent 2007). We assumed that the timber was supplied from sustainably managed forests, and that regeneration was undertaken on all cutting sites, i.e. that no land transformation is taking place in a long-term perspective. The average transport distance to forest sites was assumed to be 20 km (one way), both for forestry machines and operators for all processes with the exception of felling with cable cranes, where the transport distance for forestry machines was 100 km (Vennesland et al. 2013). Transport of goods was expressed in ton kilometres (tkm), which is defined as the product of the quantity of goods transported and the transport distance (Ecoinvent 2007). In order to analyse GHG emissions from Norwegian forestry, we built 13 processes based mostly on primary and secondary data from Norwegian sources. Primary data were either gathered directly from forest owners, companies and industries by Vennesland et al. (2013) or resulted from time studies of forestry machines and operations conducted in the forest by Vennesland et al. (2013) to measure efficiency and fuel consumption. Secondary data (statistics) were mainly retrieved from the Norwegian Agricultural Authority (SLF 2012) and Statistics Norway (SSB 2012) and were based on average numbers for 2010. Due to the lack of specific Norwegian forestry data in Ecoinvent, we designed and constructed unit processes based on these primary and secondary data, especially for transport distances, fuel consumption and forestry machinery. Time studies of workers and machines were used in all forestry processes as basis for calculating GHG emissions. Selected Ecoinvent unit processes were modified and supplied with specific Norwegian data. The Ecoinvent process *Tractor, production* was used as a proxy for forestry machines (forwarder, harvester and cable crane). It was modified with the weight and service life of the machines, given by 17 metric tons (t) and 15,000 hours (h) for a forwarder and 20 t and 15,000 h for a harvester. The Ecoinvent process *Transport, passenger car*, used for the transport of operators and workers to the forest, was modified to yield vehicle kilometres (vkm) instead of person kilometres (pkm) in order to reflect the distance a car is driven irrespective of how many persons are in the car, assuming that teams of forest workers will travel in one car to the forest sites (Vennesland et al. 2013).

2.3 System boundaries

Calculations of GHG emissions were conducted on fossil-related inputs from the technosphere only. CO_2 emissions from decomposition of organic materials (both above-ground and below-ground) as a consequence of the final felling were excluded from the inventory on the assumption that biogenic CO_2 is neutral because the CO_2 will be sequestered again by growing trees (US EPA 2006). No attempts were made to consider the impact of Norwegian forestry on biodiversity and forest ecosystems. Planning of silvicultural and other forestry activities was not considered in the present study due to the scarcity of data from East Norway. In contrast to Sweden and Finland, most of the forest residues like stumps, branches and tops are left in the forest after final felling in Norway, and only a small fraction is used for bioenergy. The utilisation of forest residues was therefore not considered in the present study. Transport of timber by cargo ships along the Norwegian coast was not included in this analysis since it is not a common way of transport within the examined region. Export and import of timber was beyond the scope of the present study. Neither by-products from the sawmill industry like bark, sawdust and chips, nor other industrial wood processing were included in the present analysis (Fig. 1).

2.4 Inventory

2.4.1 Seed and seedling production

According to The Norwegian Forest Seed Centre (Skogfrøverket 2012), 210 kg seeds were sold to forestry nurseries in East Norway in 2010. The proportion of Norway spruce seeds was 75 %, almost all from seed plantations, other conifer seeds accounted for 15 % and seeds from deciduous species for 10 %. The use of heating oil and electricity for seed production was included in the seed production process. Reforestation in East Norway required 14 million seedlings that were produced in 7 forestry nurseries in 2010 (SLF 2012). Data from Flæte (2009) and Aldentun (2012) were incorporated in the seedling production process adapted for Norwegian requirements. Calcium ammonium nitrate (CAN) was used as fertilizer for seedling production. The use of energy, fuel, fertilizer and insecticides during seedling production was accounted for in the process.

2.4.2 Site preparation (scarifying)

Site preparation is the first step in afforesting a clear-cut site. Scarifying the top soil layer will remove competing vegetation, prepare the ground for planting and is thus supposed to increase seedling survival and thereby timber yield. Site preparation is done mechanically, mostly with a forwarder or a heavy tractor with special scarifying equipment mounted. According to time studies carried out by Vennesland et al. (2013), scarifying 1 ha of clear-cut area took 2 h with a forwarder with a diesel consumption of 48 litres (l) per ha. Site preparation was carried out on 3,526 ha of regeneration sites in the eastern Norwegian region in 2010 (SLF 2012).

2.4.3 Reforestation

Reforestation should be carried out immediately after felling in order to utilize the nutrients that are exposed from forest residues, and, according to Norwegian forestry regulations (LMD 2006), no later than 3 years after felling. Large areas, however, especially pine stands, are prepared for natural regeneration by seeds from seed trees. Two-year-old spruce seedlings from forestry nurseries are commonly used for reforestation. The normal planting density for spruce is 1,700 seedlings per ha. Three workers used 4.5 h to plant 1 ha with seedlings (Vennesland et al. 2013). The transport of the seedlings from the nursery to the forest site with an average transport distance of 50 km was included in the reforestation process. The afforested area in East Norway was 8,263 ha in 2010 (SLF 2012).

2.4.4 Tending

Tending of young stands, also called juvenile spacing, is an important silvicultural operation and, done properly, it may increase both timber quality and yield. Tending aims at removing competing vegetation and, above all, at reducing the total number of trees in the stand so that only superior trees of the most desirable species are left. It will also provide enough space between individuals for optimal growing conditions. Tending should be carried out while the trees are between 1.3 and 4 m tall, and usually clearing saws are used. Teams of two or more workers were operating together in a stand, using 5 h to tend 1 ha of juvenile forest according to time studies by Vennesland et al. (2013). Tending is quite common in Norway, and 20,386 ha of young forest stands were tended in the eastern region in 2010 (SLF 2012).

2.4.5 Spraying

Spraying of forests with herbicides is done in order to remove competing vegetation, in particular grasses, herbs and deciduous trees. Usually, herbicides are sprayed from a helicopter on young forest stands. The quantity of 3.5 l of glyphosate (Roundup), diluted in water, was applied in roughly 2 minutes (min) per ha (Vennesland et al. 2013). Spraying of forests is not a very common operation in Norwegian forestry and is subject to severe restrictions. A good alternative to spraying is tending of young stands. In 2010, spraying was carried on an area of 592 ha in the assessed region (SLF 2012).

2.4.6 Fertilization

Fertilization will have best effect on growth and yield if applied 6–10 years before the final felling. Growth will increase approximately by 1–2 m^3/ha and year, depending on site conditions. However, a presumable increase in growth from fertilization was not taken into consideration in the present study since the fertilized area in 2010 was rather small. CAN fertilizer with a nitrogen content of 27 % is used. The recommended amount of CAN is 550 kg/ha in order to achieve optimum yield (SKI 2005). A helicopter was measured to disperse the fertilizer in 3 min per ha (Vennesland et al. 2013). Fertilization is not customary in Norwegian forests. The fertilized forest area in 2010 was 547 ha in the assessed region (SLF 2012).

2.4.7 Pruning

The purpose of the pruning operation is to increase the timber quality by reducing the amount of branches, which results in clean, knot-free wood. Pruning is done manually with pruning shears, mostly on pine. Teams of two workers operated together in a stand, and according to time studies, they used 20 h

for pruning 1 ha of forest (Vennesland et al. 2013). It is not widely in use in Norway nowadays. In 2010, pruning was undertaken on a forest area of approximately 336 ha in East Norway (Vadla 2011).

2.4.8 Forest road construction and upgrading

In 2010, 36 km of new forest roads were constructed, and 223 km of existing forest roads were upgraded in East Norway (SLF 2012). GHG emissions from the construction of forest roads before 2010 have not been considered, even though these roads are still in use. To prepare the site for road building, trees are felled with a harvester and stumps and soil are removed with a digger. Finally, gravel is levelled out with a digger and a bulldozer (a skid-steer loader was used as a proxy in the present study). The average length of the construction sites in 2010 was 0.8 km for newly built roads and 1.4 km for upgraded roads (SSB 2012). Standard width of a Norwegian forest road is 4 m. The amount of 1,800 t of gravel was used for the construction and 600 t for the upgrading of 1 km of forest road, transported over a distance of 20 km from the quarry to the forest. Technical data on the operation of the machines were retrieved from The Forestry Research Institute of Sweden (Skogforsk 2010).

2.4.9 Thinning and forwarding

Thinning is carried out with a harvester. The purpose of thinning is to reduce the number of trees in the stand in order to give the remaining trees better growing conditions. Timber was transported from the forest site to the nearest forest road with a forwarder over an average distance of 300 m (Vennesland et al. 2013). The loading and unloading of the forwarder was included in the operation and diesel consumption of the forwarder. Time studies conducted during thinning by Vennesland et al. (2013) showed that a harvester had to operate for 13 min, corresponding to 1.87 l of diesel consumption, to extract 1 m^3 of timber. A forwarder had to operate for 6 min with a diesel consumption of 1.01 l/m^3 of timber. The total timber yield from thinning in East Norway was calculated to be 1 million m^3 in 2010.

2.4.10 Final felling and forwarding

The final felling is in most cases carried out with a harvester as a clear cut based on sustainable management principles and Norwegian forestry regulations (LMD 2006). The area of an average clear-cut site in Norway was 5 ha in 2010, and the average forwarding distance was 500 m (Vennesland et al. 2013). The process of loading and unloading of the forwarder was included in the operation and diesel consumption of the forwarder. The operating time of a harvester per m^3 of timber was measured to be 4 min with a diesel consumption of 0.85 l. The forwarder operational time was measured to be 4 min with a diesel consumption of 0.82 l per m^3 of timber (Vennesland et al. 2013). The total timber yield from final felling in East Norway was calculated to be 5.55 million m^3 in 2010.

2.4.11 Other practices of harvesting

Other methods of harvesting include the use of cable cranes in steep terrain and small diameter tree harvesting for bioenergy. Large parts of the Norwegian landscape are hilly and undulated and are considered as very difficult for forestry. When felling in steep and difficult accessible terrain, trees are cut with a chain saw in the forest and transported to the logging site by a cable crane. Two systems are used in Norway (Vennesland et al. 2013). When using an Owren 400 cable crane, a harvester is applied in addition to remove branches and cut the logs, and a forwarder to pile the logs. The Mounty 3000 system has both a cable crane and a harvester mounted on a truck, and no forwarder is used. The weight of an Owren 400 is 24 t, and that of a Mounty 3000 26 t. Measurements from time studies indicated that felling by the use of cable cranes had low efficiency in comparison to clear-cutting with a harvester due to the difficult terrain conditions and the use of both chain saws and several heavy machines (Vennesland et al. 2013). These findings were incorporated in the cable crane felling process. According to SLF (2012), 1.1 % (0.07 million m^3) of the timber volume in 2010 was harvested by the use of cable cranes in steep terrain in East Norway. Small diameter tree harvesting for bioenergy use was mainly done in connection with the final felling, and accounted for 0.9 % (0.06 million m^3) of the timber volume in 2010 in East Norway (SLF 2012). Chipping of the biomass and transport of chips were not included in this assessment.

2.4.12 Timber transport, road

In Sweden, it is common to use 60-t logging trucks, and from September 2013, 60-t trucks are also allowed in Norway (Ministry of Transport and Communications 2013). However, the maximum weight capacity of many Norwegian roads and bridges is only 56 t or even less, thus limiting an expanded use of larger trucks. In 2010, the average load of a Norwegian logging truck with trailer was 37 m^3, corresponding to a total vehicle weight of 48 t (Vennesland et al. 2013). This load, as well as the average fuel consumption of Norwegian logging trucks, which was measured to be 0.58 l/km (Vennesland et al. 2013), was used to design the road transport process. The volume weighted mean transport distance in East Norway with trucks was 58 km for saw timber and 69 km for pulpwood in 2010 (Vennesland et al. 2013). The load factor was 50 %, meaning that a full-loaded truck delivered the timber at the factory gate and returned to the logging site without load.

In 2010, 3.49 million m^3 of the total timber yield was saw timber and 3.19 million m^3 pulpwood (SLF 2012). Almost all of the saw timber was transported by truck directly to the nearest saw mill. In contrast, only 61 % of the pulpwood was transported directly by truck to wood processing factories, while 39 % of the pulpwood was first transported by truck to a railway freight terminal; thereafter, long-distance transport was done by rail (SLF/JBV 2010). The loading and unloading of the logging trucks with a diesel consumption measured to be 0.30 l/m^3 timber (Vennesland et al. 2013), was included in the road transport processes.

2.4.13 Timber transport, rail

In 2010, 19 % (1.27 million m^3) of all timber was transported by rail in addition to the road transport. The volume of pulpwood transported by train was 39 % (1.24 million m^3), whereas only 0.9 % of the saw timber (0.03 million m^3) was shipped on rail (SLF/JBV 2010). Based on the lack of more precise data, we assumed the same transport distance for both saw timber and pulpwood. The average transport distance of timber was 250 km with electric trains and 130 km with diesel trains, data given for 2010. Only a small fraction of the harvested timber (0.04 million m^3) was transported by diesel trains, whereas 1.23 million m^3 of timber were transported by electric trains (Vennesland et al. 2013). The average Norwegian timber train had a length of 400 m and could take a load in the range from 800 to 1,000 m^3 of timber (SLF/JBV 2010). This specific load of the Norwegian timber trains was not taken into consideration, although it presumably is smaller than that of an average European freight train (Ecoinvent 2007). The loading and unloading of the trains was carried out with a hydraulic digger with a diesel consumption measured to be 0.12 l/m^3 timber (Vennesland et al. 2013), which was included in the rail transport processes. Electric trains were running on Nordic electricity mix (NORDEL), diesel trains were assumed to have no particle filters.

3 Results and discussion

GHG emissions from the forestry supply chain in East Norway in 2010 are presented in detail in Table 1. The sum of fossil-related GHG emissions, expressed as metric ton CO_2-equivalents, was calculated for each analysed process from seed production to industry gate. Subsequently, GHG emissions for the functional unit of 1 m^3 extracted timber were calculated in kilogram CO_2-equivalents for all the assessed processes. Net emissions of the three most important GHGs, namely CO_2, N_2O and CH_4, are also presented in Table 1, expressed as kg/m^3 of extracted timber. The sensitivity analysis conducted in SimaPro showed small relative standard deviations (coefficient of variation) from the mean GHG emissions for most grouped processes and for the sum of all processes (Table 1). Coefficients of variation were in the range of 6.6 to 8.0 % for most processes, with the exception of the forest roads and rail transport processes, ranging from 15.8 to 24.0 %. The sensitivity analysis revealed that statistical errors were rather small in the present study.

GHG emissions from the extraction and transport of 6.68 million m^3 timber in East Norway, including all the assessed processes from seed production and silviculture to final felling and transport of timber to the consumer, amounted to almost 120,000 t of CO_2-equivalents in total, or 17.893 kg CO_2-equivalents per m^3 of timber delivered to industry gate in 2010 (Table 1). The emissions per m^3 of extracted and delivered timber for the grouped forestry processes were 0.538 kg from silviculture (including seed and seedling production), 0.308 kg from forest road building, 1.892 kg from thinning and forwarding, 5.528 kg from final felling and forwarding, 0.292 kg from other practices of harvesting, 8.489 kg from road transport and 0.846 kg from rail transport (Table 1).

Net total emissions of fossil CO_2, N_2O and CH_4, respectively, were 17.00, 0.00083 and 0.023 kg/m^3 of extracted and delivered timber (Table 1). Other compounds, such as ethane and other hydrocarbons, accounted for the emission of 0.088 kg CO_2-equivalents. On the basis of data given in Søgaard and Granhus (2012) and Astrup et al. (2010), it can be calculated that 1 m^3 of spruce timber is binding 733 kg of CO_2, 1 m^3 of pine timber 807 kg of CO_2 and 1 m^3 of birch timber 935 kg of CO_2. The net CO_2 emissions of 17 kg fossil CO_2 from 1 m^3 of timber extracted and delivered to industry gate in the assessed forestry chain corresponded to 2.3 % of the CO_2 sequestered by 1 m^3 of growing forest trees, given the proportion of 76, 23 and 1 % of felled spruce, pine and birch timber, respectively, in East Norway.

Based on over 400 individual studies, the review performed by Nave et al. (2010) found an average loss of 20 % of organic soil carbon from the forest floor (O horizon) on Spodosols (Podzols) in temperate forests as a consequence of harvesting, while the mineral soil was not significantly affected. Their results indicated that it will take 50–70 years to recover this loss. The length of the recovery period in boreal forests is uncertain. In spite of a substantial lack of data on the long-term recovery of the soil carbon stock in boreal forests and the optimal length of stand rotations on different soil types, the results from Nave et al. (2010) showed that a permanent loss of soil carbon of up to 20 % might be the consequence if stand rotations are shorter than the recovery period. Calculations made by de Wit and Kvindesland (1999) on the soil carbon content in Norwegian forest based on soil samples from 1,000 countrywide plots revealed that mature spruce forests had an average carbon content in the forest floor of 7 kg/m^2, and mature pine forests of 4.9 kg/m^2. Using these results and assuming a 20 % short-term (30 year) loss of this

Table 1 GHG emissions from forestry in East Norway in 2010 allocated to single and grouped processes

Process	CO_2-eq.sum t	CO_2-eq.kg/m^3	Mean±SD	CO_2kg/m^3	N_2Okg/m^3	CH_4kg/m^3
Seed and seedling production	1,228	0.184		1.7E-01	2.8E-05	2.4E-04
Site preparation	636	0.095		9.1E-02	2.9E-06	1.1E-04
Reforestation	116	0.017		1.7E-02	6.3E-07	2.1E-05
Tending	865	0.129		1.1E-01	3.6E-05	1.3E-04
Spraying	24	0.004		3.4E-03	7.3E-08	8.1E-06
Fertilization	716	0.107		3.6E-02	2.3E-04	7.3E-05
Pruning	9	0.001		1.3E-03	5.1E-08	1.7E-06
Silviculture, sum	3,594	0.538	$0.539^{+0.056}_{-0.046}$	4.3E-01	3.0E-04	5.8E-04
Forest roads, construction	699	0.105		1.0E-01	3.4E-06	1.3E-04
Forest roads, upgrading	1,361	0.204		1.9E-01	6.5E-06	2.5E-04
Forest roads, sum	2,060	0.308	$0.308^{+0.086}_{-0.051}$	2.9E-01	9.9E-06	3.7E-04
Thinning	8,334	1.247		1.2E+00	3.7E-05	1.6E-03
Timber forwarding, thinning	4,309	0.645		6.2E-01	1.9E-05	7.8E-04
Thinning, sum	12,643	1.892	$1.890^{+0.14}_{-0.12}$	1.8E+00	5.6E-05	2.3E-03
Final felling	18,721	2.801		2.7E+00	8.4E-05	3.3E-03
Timber forwarding, final felling	18,222	2.727		2.6E+00	8.2E-05	3.2E-03
Final felling, sum	36,944	5.528	$5.530^{+0.45}_{-0.37}$	5.3E+00	1.7E-04	6.6E-03
Cable crane, felling in steep terrain	1,395	0.209		2.0E-01	8.1E-06	2.5E-04
Small diameter tree harvesting	557	0.083		8.0E-02	2.4E-06	1.0E-04
Other practices of harvesting, sum	1,951	0.292	$0.292^{+0.025}_{-0.019}$	2.8E-01	1.1E-05	3.5E-04
Saw timber transport, road	27,401	4.100		3.9E+00	1.2E-04	5.3E-03
Pulpwood transport, road	29,332	4.389		4.2E+00	1.3E-04	5.7E-03
Road transport, sum	56,733	8.489	$8.490^{+0.66}_{-0.58}$	8.1E+00	2.6E-04	1.1E-02
Saw timber transport, rail	140	0.021		2.0E-02	8.2E-07	4.0E-05
Pulpwood transport, rail	5,516	0.825		7.7E-01	3.2E-05	1.6E-03
Rail transport, sum	5,656	0.846	$0.845^{+0.167}_{-0.125}$	2.0E-02	8.2E-07	4.0E-05
SUM	119,581	17.893	$17.894^{+1.2}_{-1.2}$	1.7E+01	8.3E-04	2.3E-02

The sum of silviculture includes seed and seedling production. Sum emissions of CO_2-equivalents in metric tons for each process (CO_2-eq. sum t); CO_2-equivalents in kg/m^3 of extracted timber (CO_2-eq. kg/m^3), net CO_2, N_2O and CH_4 in kg/m^3 of extracted timber. Standard deviations (SD) from the mean GHG emissions are given for the grouped processes

amount, the maximum release of soil carbon from the forest floor as a direct consequence of harvesting was re-calculated to correspond to circa 47 t CO_2 per ha of a mixed coniferous forest stand in East Norway, or to 170 kg biogenic CO_2 per m^3 of extracted timber. This amount of biogenic CO_2 corresponded to 22.7 % of the CO_2 sequestered by 1 m^3 of growing forest trees, i.e. 10 times as much as the fossil-related emissions analysed in the present study. Even the assumption of a 2 % long-term (100 years or more) carbon loss from the forest floor was calculated to correspond to 17 kg biogenic CO_2 per m^3 of extracted timber, i.e. the same amount as the fossil-related emissions. However, since long-term carbon losses from the forest floor are highly uncertain as pointed out by Nave et al. (2010), and recovery is depending on the length of the stand rotation, the calculation for a long-term scenario of soil carbon loss is not reliable.

There are recent studies pointing out that biogenic CO_2 from forest residues used for bioenergy should not be considered as neutral (Sathre and Gustavsson 2011; Guest et al. 2013; Holtsmark 2013). Considering that these residues mostly are not used in Norway, no GHG emission calculations on their use for bioenergy purposes were included in the present study. The decomposition of forest residues after clear-cutting will in a short-term perspective add further biogenic CO_2 emissions to the total. However, in the present study, climate impacts of forest residues left at the logging site were assumed to be equal to the decomposition of biomass ongoing in an unmanaged forest in a long-term perspective and were

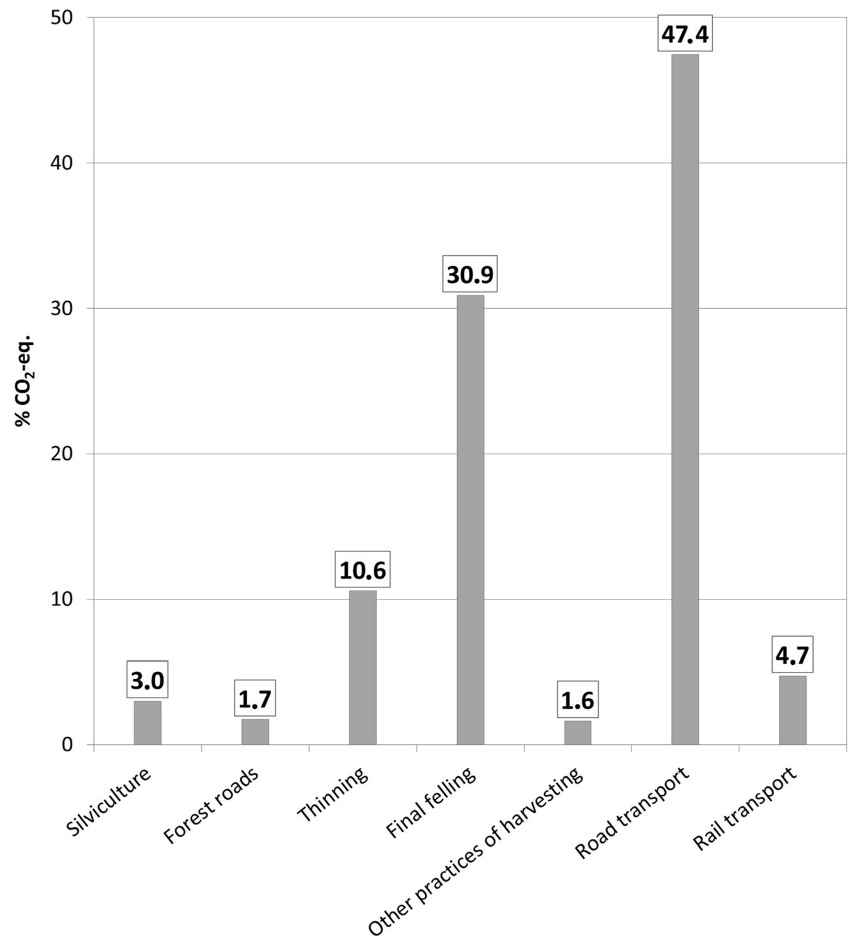

Fig. 3 Emissions of GHGs in percent CO_2-equivalents (% *CO_2-eq.*) allocated to grouped forestry processes in 2010

therefore not calculated on. Moreover, as pointed out by Nave et al. (2010), leaving the residues in the forest after harvesting may have a positive impact on nutrient and water budgets, as well as on the total carbon budget of the forest stand.

The relative contributions of the grouped forestry processes are disposed in Fig. 3, showing that almost half (47.4 %) of the total GHG emissions in the present inventory were generated by transporting 6.68 million m^3 of timber with logging trucks from the forest to the nearest industry gate or railway freight terminal, while the rail transport of 1.27 million m^3 timber accounted for only 4.7 % of the total GHG emissions, the main part of this amount (98 %) deriving from pulpwood transport. As can be seen from Fig. 3, nearly one third (30.9 %) of the total GHG emissions originated from the final felling and forwarding processes, while thinning and forwarding amounted to 10.6 %, and other methods of felling (use of cable crane in steep terrain and bioenergy harvesting) accounted for 1.6 %. Silviculture inclusive seed and seedling production summed up to 3.0 %, and the construction and upgrading of forest roads to 1.7 % of the total GHG emissions from forestry in East Norway in 2010. The study by Michelsen et al. (2008) on the environmental impact of forestry in the northern parts of Norway obtained similar relative contributions to GHG emissions from timber forwarding and road transport as in the present study, while the absolute emissions of CO_2-equivalents from these processes were considerably higher in the northern than in the eastern parts of Norway due to longer forwarding and transport distances in the north.

The presented results showed that the road transport of pulpwood produced higher GHG emissions per m^3 of transported timber than saw timber due to the longer average transport distance for pulpwood. In addition to the road transport, a substantial proportion of the pulpwood is transported long distances by railway. Final felling and forwarding generated nearly one third of the total GHG emissions, half of which is from forwarding alone (Table 1). The study by Michelsen et al. (2008) used an average forwarding distance of 740 m for both thinning and final felling in the northern parts of Norway, resulting in 1.4 times higher CO_2-emissions per m^3 harvested timber from forwarding than in the present study with 300 and 500 m of forwarding distance for thinning and final felling, respectively. Shorter distances for forwarding of timber from the forest site to the nearest forest road would decrease GHG emissions from forwarding, but on the other hand more forest roads need then to be built. The construction

of forest roads, however, is a demanding process, both in terms of investments (SSB 2012), forest land transformation and GHG emissions. According to our calculations, the construction of 1 km new forest road led to the emission of almost 20 t of CO_2-equivalents and upgrading of existing forest roads to 6 t/km. While the total contribution of forest road building and upgrading to the total GHG emissions from forestry with 1.7 % is small in East Norway (Fig. 3), Michelsen et al. (2008) found it to be as much as 8.1 % in Northern Norway.

The study by Mäkinen and Isomäki (2004) stated that final felling is more efficient than thinning in terms of timber yield. Based on the sum of GHG emissions from thinning and the timber yield, it can be calculated that thinning led to almost 2.5 times as high GHG emissions as final felling per m^3 of timber harvested. From an economical point of view, thinning has the advantage that it creates an income for the forest owner at an early stage of the rotation period (Cao et al. 2008). However, the data provided by Vennesland et al. (2013) indicated that the costs for the thinning operations were more than twice as high per 1 m^3 of harvested timber as for the final felling in 2010. Also in terms of forest management, there are ongoing discussions in Norway, as well as in other Nordic countries, if thinning really is increasing timber quality and yield (Mäkinen and Isomäki 2004; Eriksson 2006; Cao et al. 2008). In many cases, an improvement in timber quality in order to rise the proportion of saw timber and an increase in yield can be achieved at lower costs by tending and cleaning the young stands, maybe repeatedly at different growth stages, rather than by thinning (Tveite and Braastad 2000; Eriksson 2006). This change in management practice would also contribute to a reduction in GHG emissions from forestry by reducing thinning activities and road transport.

The results of the present study indicated that felling with cable cranes led to almost three times as high GHG emissions as final felling per m^3 of timber extracted. However, since the timber yield from felling with cable cranes was only about 1 % of the total quantity of timber harvested in East Norway, its contribution to the total GHG emissions from forestry was low (Table 1).

Generally, it is assumed that an increase in size of transport vehicles could decrease fuel consumption per transported volume and thereby also costs. A calculation of GHG emissions in kg CO_2-equivalents per tkm for different means of transport is illustrated by Fig. 4. The standard Ecoinvent truck *Lorry>16 t* was included to show the impact of precise fuel consumption data on the final result. The Ecoinvent truck was compared to trucks of 48 t, 56 t and 60 t, which are modified processes with a fuel consumption of 0.58, 0.62 and 0.65 l/km, respectively, calculated for Norwegian conditions and based on the assumption that a 50 % increase in load leads to a 25 % increase in fuel consumption. The ship used for the comparison was a medium-sized freight ship with a load of 5,000 m^3, a load factor of 62.5 % and a fuel consumption of 22.1 l/km (Nørstebø et al. 2011). The train was running on a mixture of electricity and diesel as applied in this study. The calculation showed that increasing the truck size to 56 and 60 t reduced CO_2 emissions from timber transport by 12 and 17 %, respectively, compared to the 48-t truck used in present study. Löfroth and Svenson (2012) showed that CO_2 emissions from timber transport in Sweden could be reduced by 20 % when increasing truck size from 60 to 90 t. Furthermore, the data presented in Fig. 4 show that transporting timber with the smallest truck (48 t) generated more than six times as high GHG emissions as transporting timber by train, and even the largest truck (60 t) led to more than five times as high GHG emissions as the train. Assuming that rail transport of timber in Norway could expand, this would lead to reduced GHG emissions and consequently to lower life cycle costs compared to road transport with logging trucks. However, there are factors hindering increased timber transport by railway in Norway. The infrastructure in terms of side railways to industry gates and freight terminals close to forest sites is insufficient, and rail transport is only cost efficient when the distance is longer than 130 km (SLF/JBV 2010).

In addition to the way of transport, the distance for the timber transportation from forest site to final consumer is an important factor. The critical situation of closing down parts of the Norwegian wood industry that has taken place over the last years (Dagsavisen 2013; e24.no 2013) might probably have led to increased transport distances for both saw timber and pulpwood and hence higher GHG emissions, as well as costs. If there finally are too few industrial consumers in Norway, the timber presumably has to be exported, thereby further increasing transport distances, GHG emissions and also costs. Economic factors like market demands, timber and product price development and other costs strongly affect wood industry and transport sector. An analysis of the flows from and between the different parts of the wood industry requires to consider these factors which are usually outside the system boundary of an attributional LCA. The approach of a consequential LCA takes into consideration implications of changes in the economic sphere and may thus provide a sounder basis for decision making on how to minimize GHG emissions (Plevin et al. 2014). Such an analysis, however, was outside the scope of the present study.

Even though the primary focus of this study was on climate change as the main impact category, the examined forestry chain had impact on other environmental categories as well. Figure 5 illustrates the relative contribution of the analysed processes on the impact categories *climate change*, *ozone depletion*, *human toxicity*, *particulate matter formation*, *terrestrial acidification*, *freshwater eutrophication*, *marine eutrophication* and *natural land transformation*. Emissions generated by the road transport processes contributed most to all environmental impact categories, while the final felling and forwarding processes had the second highest contribution.

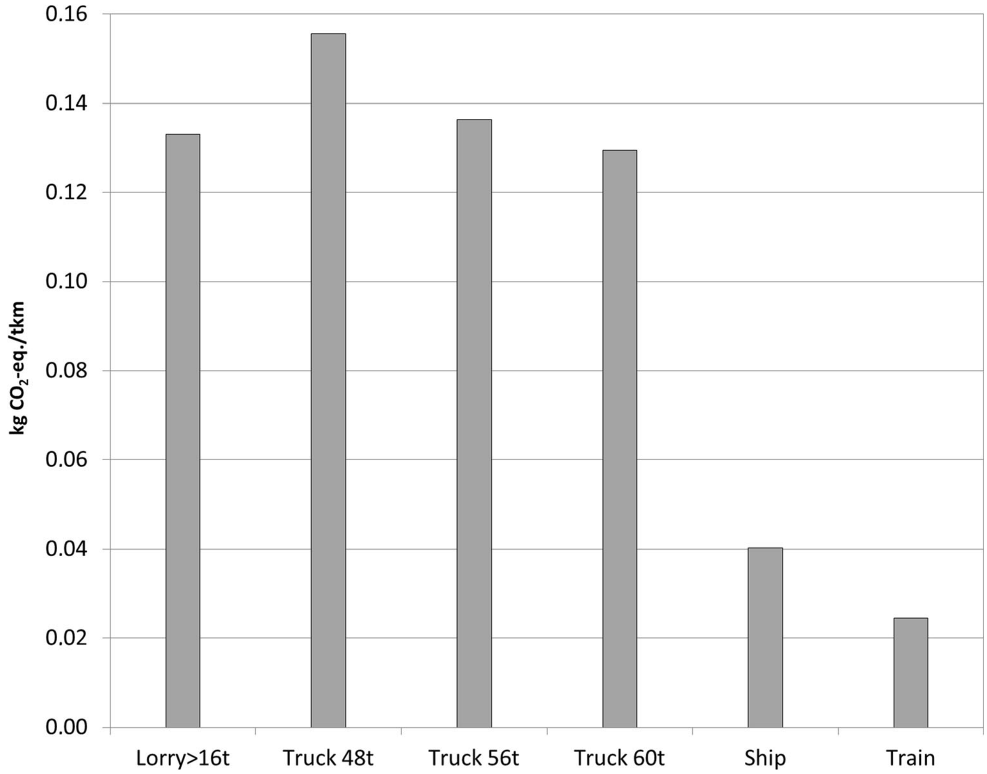

Fig. 4 Calculation of GHG emissions in kilogram CO_2-equivalents per ton kilometre (*kg CO_2-eq./tkm*) for different means of transport. Loading and unloading is not included

Obviously, the environmental impact of forestry on all categories was mainly caused by fuel (diesel) combustion processes from vehicles within transport and from heavy forestry machines used for felling and thinning. Under the assumption that all cutting sites are afforested, final felling had little impact on natural land transformation in a long-term perspective. Short-term impacts of clear-cutting on biodiversity were not considered in the present study. The need for methods dealing with these topics is discussed in Michelsen (2008) and Michelsen et al. (2012). The approach by Michelsen et al. (2012), using the amount of deadwood and land use change as indicators for impacts on biodiversity, is interesting and could be elaborated further using specific data from the Norwegian Forest Inventory. The construction of new forest roads had the highest impact on the category of natural land transformation (Fig. 5) as these roads are built for permanent use. As an indirect consequence, the construction of new forest roads into remote areas might lead to logging activities in forests formerly not intensively utilized, probably with a high impact on biodiversity.

In Table 2, the absolute contribution of the analysed grouped forestry processes are listed for selected environmental impact categories. In the category climate change, which the present study mainly has focussed on, combustion of fuel was the most important contributor to GHG emissions. The category human toxicity is expressed in 1,4 dichlorobenzene (1,4 DB) equivalents, and the analysed forestry processes generated almost 17,000 t of 1,4 DB-equivalents, mostly from the use of heavy metals in different underlying production processes in Ecoinvent. Half of the emitted 1,4 DB-equivalents originated from the use of manganese in the production of iron and steel, which are used in the fabrication of vehicles and forestry machines. In this impact category, rail transport contributed proportionally more than in the other categories due to the extensive use of iron and steel in the production of both wagons and infrastructure (rails). Emissions of particulate matter (PM10), sulphur dioxide (SO_2) and nitrate (NO_3) equivalents seemed to be directly correlated to fuel combustion, as was the case for GHG emissions.

4 Conclusions and recommendations

GHG emissions from forestry in East Norway were calculated for 1 m^3 timber extracted and delivered to industry gate in 2010. The road transport of timber had the highest impact on the climate change category. Increasing logging truck size and the proportion of railway transport may result in lower GHG emissions per volume of transported timber. Improving timber quality to achieve a higher proportion of saw timber instead of pulpwood might also reduce transport distances and thereby GHG emissions. Intensive forest management in East Norway, especially in central parts that have been object to intensive harvesting before, may reduce forwarding and transport distances and the need for new forest roads, and may thus

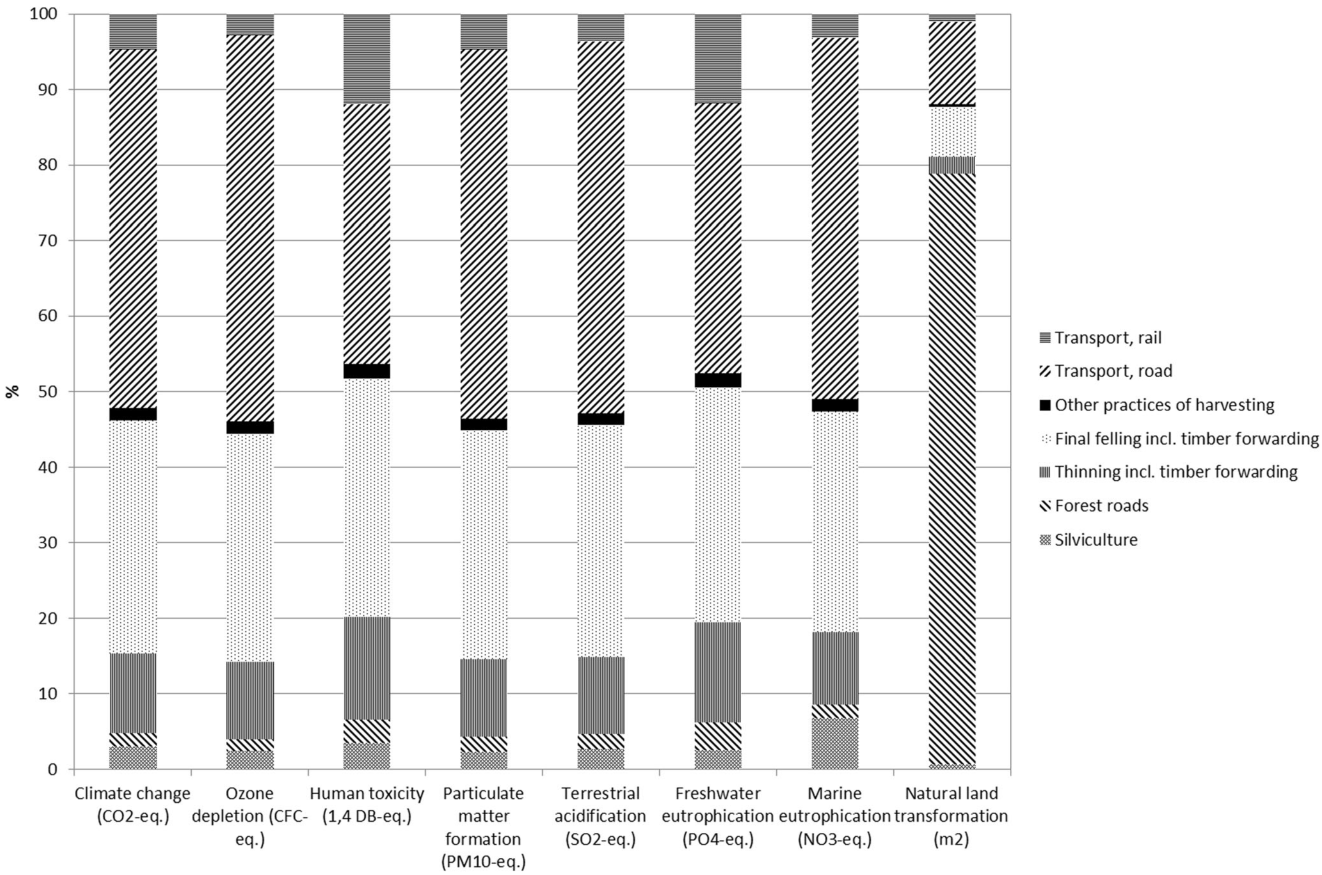

Fig. 5 The relative contribution of the analysed grouped forestry processes on selected environmental impact categories in percentages (*eq.*= equivalents, CO_2=carbon dioxide, *CFC*=chlorofluorocarbon gases, *1,4-DB*=1,4 dichlorobenzene, *PM10*=particles<10 µm, SO_2=sulphur dioxide, PO_4=phosphate, NO_3=nitrate)

generate less GHG emissions than timber extraction in other parts of Norway. Building of new forest roads into remote areas might open access to forests formerly not intensively managed, probably with high impact on biodiversity. Some processes, like the building of forest roads and the use of cable cranes for felling in steep terrain, generate high GHG emissions, but as long as these activities remain at a low level in proportion to the total amount of yearly harvested timber, their contribution to the total GHG emissions from forestry is small. A LCA of forestry may also consider the impact of forestry operations, the production of vehicles and machines and the combustion of fuel on environmental categories other than climate change. Biogenic CO_2 emissions from the soil compartment as a consequence of harvesting may be up to 10 times higher than the fossil-related emissions, at least in a short-term perspective, and are highly dependent on the length

Table 2 The absolute contribution of the analysed grouped forestry processes on selected environmental impact categories in metric tons (t) of equivalents (for abbreviations see caption in Fig. 5)

Process	Climate change t CO_2-eq.	Ozone depletion t CFC-eq.	Human toxicity t 1,4-DB-eq.	Part. matter formation t PM10-eq.	Terrestrial acidification t SO_2-eq.	Freshwater eutrophic. t PO_4-eq.	Marine eutrophic. t NO_3-eq.
Silviculture	3,594	0.0004	588	7	18	0.3	2.8
Forest roads	2,060	0.0003	524	6	13	0.5	0.8
Thinning	12,643	0.0018	2,274	30	69	1.6	4.0
Final felling	36,944	0.0053	5 324	90	205	3.9	12.2
Other harvesting	1,951	0.0003	316	5	11	0.2	0.7
Transport, road	56,733	0.0090	5 809	145	329	4.4	19.9
Transport, rail	5,656	0.0005	2 009	14	24	1.5	1.4
SUM	119,581	0.0176	16 845	297	669	12.4	41.8

of stand rotations. The methodology applied in SimaPro uses a time horizon for impact categories of 100 years; however, it is acknowledged that some environmental impacts may be realized much later than that, and LCA studies might therefore need to consider longer time frames.

Further examination of the actual service life of forest machines and their maintenance may be required. A more detailed study of the life span of forest roads and their actual extent and frequency could be conducted in order to determine their contribution to the total GHG emissions more accurately. Upgrading of existing forest roads in easily accessible, central areas should be prioritised over the building of new roads. Data from the Norwegian Forest Inventory could be used to calculate more precise forwarding distances for each county, and to design an indicator for impacts of forestry on biodiversity based on changes in land use and in the amount of deadwood. Long-term losses of soil carbon after harvesting should be investigated further. It would be useful to develop species-specific models for climate-optimal stand rotation length on different soil types in Norwegian forests to counteract biogenic CO_2 emissions from the forest floor. The release of organic soil carbon as a consequence of harvesting should also be taken into consideration to improve forest management practices.

Acknowledgments The Norwegian Forest and Landscape Institute and the project KlimaTre (funded by The Research Council of Norway, grant number 199332) provided the financial support required to undertake this study. The authors would like to thank Leif Kjøstelsen for conducting numerous field studies and Anders Møyner Eid Hohle for providing required data for forestry operations. The authors are grateful to Lars Gunnar Tellnes, Lone Ross Gobakken, Gry Alfredsen and Bruce Talbot for their various contributions, helpful comments and suggestions. Sincere thanks are given to Holger Lange and Janne Kjønaas for their contributions to the statistical analysis and the soil carbon matter, respectively.

References

Abbott J (2008) What is a carbon footprint? Report. The Swedish Forest Industries Federation and Timcon. The Edinburgh Centre for Carbon Management

Aldentun Y (2012) Life cycle inventory of forest seedling production-from seed to regeneration site. J Clean Prod 10(1):47–55

Astrup R, Dalsgaard L, Eriksen R, Hylen G (2010) Utviklingsscenarioer for karbonbinding i Norges skoger (Development scenarios for carbon sequestration in Norwegian forests). Norwegian Forest and Landscape Institute report 16/10

Berg S, Karjalainen T (2003) Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry 76(3):271–284

Berg S, Lindholm EL (2005) Energy use and environmental impacts of forest operations in Sweden. J Clean Prod 13:33–42

Brander M, Tipper R, Hutchison C, Davis G (2009) Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels. Technical Paper TP090403A, Ecometrica

Cao T, Valsta L, Härk nen S, Saranpää P, Mäkelä A (2008) Effects of thinning and fertilization on wood properties and economic returns for Norway spruce. For Ecol Manag 256(6):1280–1289

Dagsavisen (2013) Norsk treindustri i krise (Norwegian wood processing industry in crisis). http://www.dagsavisen.no/samfunn/norsk-treindustri-i-krise/. Published 21 March 2013, accessed 19 November 2013

De Wit H, Kvindesland S (1999) Carbon stocks in Norwegian forest soils and effects of forest management on carbon storage. Norwegian Forest and Landscape Institute report Supplement 14

e24.no (2013) Nå sendes norsk skog ut av landet (Norwegian timber is now sent out of the country). http://e24.no/naeringsliv/naa-sendes-norsk-skog-ut-av-landet/22600573. Published 4 November 2013, accessed 6 November 2013

Ecoinvent (2007) Overview and methodology. Ecoinvent report No. 1. Swiss Centre for Life Cycle Inventories. Dübendorf

Eid T, Hoen FH, Økseter P (2002) Timber production possibilities of the Norwegian forest area and measures for a sustainable forestry. For Policy Econ 4(3):187–200

Eriksson E (2006) Thinning operations and their impact on biomass production in stands of Norway spruce and Scots pine. Biomass Bioenerg 30(10):848–854

Eriksson E, Gillespie A, Gustavsson L, Langvall O, Olsson M, Sathre R, Stendahl J (2007) Integrated carbon analysis of forest management practices and wood substitution. Can J For Res 37(3):671–681

Fantozzi F, Buratti C (2010) Life cycle assessment of biomass chains: wood pellet from short rotation coppice using data measured on a real plant. Biomass Bioenerg 34:1796–1804

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manag 91(1):1–21

Fitje A (1989) Tremåling (Tree measurements). Landbruksforlaget

Flæte PO (2009) Energiforbruk og utslipp fra skogproduksjonskjeden med utgangspunkt i aktivitetsdata fra 2007 – fra frø til industritomt (Energy consumption and emissions from the forest production chain from 2007—from seeds to industry gate). Norwegian Forest and Landscape Institute working paper

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: characterisation. Ministerie van VROM. Den Haag

Granhus A, Hylen G, Nilsen JEØ (2012) Skogen i Norge. Statistikk over skogforhold og skogressurser i Norge registrert i perioden 2005-2009 (Statistics of Forest Conditions and Resources in Norway). Norwegian Forest and Landscape Institute resource overview 03/12

Guest G, Cherubini F, Strømman AH (2013) The role of forest residues in the accounting for the global warming potential of bioenergy. GCB Bioenergy 5(4):459–466

Gustavsson L, Sathre R (2006) Variability in energy and carbon dioxide balances of wood and concrete building materials. Build Environ 41(7):940–951

Hauschild M, Olsen SI, Hansen E, Schmidt A (2008) Gone… but not away—addressing the problem of long-term impacts from landfills in LCA. Int J Life Cycle Assess 13:547–554

Heath L, Maltby V, Miner R, Skog K, Smith J, Unwin J, Upton B (2010) Greenhouse gas and carbon profile of the U.S. forest products industry value chain. Environ Sci Technol 44(10):3999–4005

Holtsmark B (2013) Quantifying the global warming potential of CO_2 emissions from wood fuels. GCB Bioenergy. doi:10.1111/gcbb.12110

Jungmeier G, McDarby F, Evald A, Hohenthal C, Petersen AK, Schwaiger HP, Zimmer B (2003) Energy aspects in LCA of forest products. Int J Life Cycle Assess 8(2):99–105

Lindholm EL (2010) Energy use and environmental impact of roundwood and forest fuel production in Sweden. Dissertation, Swedish University of Agricultural Sciences

Liski J, Pussinen A, Pingoud K, Mäkipää R, Karjalainen T (2001) Which rotation length is favorable to carbon sequestration? Can J For Res 31:2004–2013

LMD (2006) FOR 2006-06-07 nr 593: Forskrift om berekraftig skogbruk (Regulation on sustainable forest management). Landbruks- og matdepartementet (Ministry of Agriculture and Food). http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20060607-0593.html. Accessed 12 March 2013

Löfroth C, Svenson G (2012) ETT – Modulsystem för skogstransporter – En Trave Till (ETT) och Större Travar (ST) (ETT – Modular system for timber transport – One More Stack (ETT) and Bigger Stacks (ST)). The Fnorestry Research Institute of Sweden working paper 758

Mäkinen H, Isomäki A (2004) Thinning intensity and long-term changes in increment and stem form of Norway spruce trees. For Ecol Manag 201(2–3):295–309

Matthews RW, Robertson K, Marland G, Marland E (2007) Carbon in wood products and product substitution. In: Freer-Smith PH, Broadmeadow MSJ, Lynch JM (eds) Forestry and Climate Change. CABI Publishing. Forest Research, Farnham, pp 91–104

Michelsen O (2008) Assessment of land use impact on biodiversity. Proposal of a new methodology exemplified with forestry operations in Norway. Int J Life Cycle Assess 13(1):22–31

Michelsen O, Solli C, Strømman AH (2008) Environmental impact and added value in forestry operations in Norway. J Ind Ecol 12:69–81

Michelsen O, Cherubini F, Strømman AH (2012) Impact assessment of biodiversity and carbon pools from land use and land use changes in life cycle assessment, exemplified with forestry operations in Norway. J Ind Ecol 16:231–242

Ministry of Transport and Communications (2013) Press release No. 100/13, 06.09.2013

Nave LE, Vance ED, Swanston CW, Curtis PS (2010) Harvest impacts on soil carbon storage in temperate forests. For Ecol Manag 259:857–866

Nørstebø VS, Johansen U, Gabriel HM, Talbot B, Nilsen JE (2011) Transport av skogsvirke i kyststrøk fra Finnmark til Rogaland (Transport of timber at the coast from Finnmark to Rogaland). SINTEF report A20874

Parigiani J, Desai A, Mariki R (2011) The carbon footprint of an East African forestry enterprise. Int J Sustain Dev 4(3):152–162

Plevin RJ, Delucchi MA, Creutzig F (2014) Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. J Ind Ecol 18(1):73–83

Salazar J, Sowlati T (2008) A review of the life-cycle assessment of windows. For Prod J 58(10):91–96

Sathre R, Gustavsson L (2011) Time-dependent climate benefits of using forest residues to substitute fossil fuels. Biomass Bioenerg 35:2506–2516

SimaPro (2008) Introduction to LCA with SimaPro 7. PRé Consultants, Amersfoort

SKI (2005) Gjødsling (Fertilization). Skogbrukets Kursinstitutt (The Forestry Extension Institute). SKI resumé 12/05

Skogforsk (2010) Vägbyggnad. Kostnader och prestationer (Road construction. Costs and efficiency). Skogforsk, Kunskap direkt (the Forestry Research Institute of Sweden, Immediate knowledge). http://www.skogforsk.se/sv/KunskapDirekt/Vagbyggnad/Kostnader-och-prestationer/#. Accessed 15 March 2013

Skogfrøverket (2012) Årsmelding 2011 (Annual report 2011). Stiftelsen Det norske Skogfrøverk (The Norwegian Forest Seed Centre)

SLF (2012) Statens landbruksforvaltning (Norwegian Agricultural Authority). https://www.slf.dep.no/no/statistikk/skogbruk. Accessed 1 November 2012

SLF/JBV (2010) Økt virkestransport på jernbane (Increased timber transport on the railway). Statens landbruksforvaltning og Jernbaneverket (Norwegian Agricultural Authority and Norwegian National Rail Administration)

Søgaard G, Granhus A (2012) Klimaoptimalt skogbruk. En vurdering av utvalgte skogskjøtseltiltak i Akershus fylke (Climate optimal forestry. A consideration of selected silvicultural operations in Akershus county). Norwegian Forest and Landscape Institute report 09/12

Solli C, Reenaas M, Strømman AH, Hertwich EG (2009) Life cycle assessment of wood-based heating in Norway. Int J Life Cycle Assess 14:517–528

SSB (2009) Skogbruk, landbruksundersøkinga 2008 (Forestry, agricultural survey 2008). Statistisk sentralbyrå (Statistics Norway)

SSB (2012) Statistisk sentralbyrå (Statistics Norway). http://www.ssb.no/jord-skog-jakt-og-fiskeri?de=Skogbruk. Accessed 1 November 2012

Trømborg E (2011) Biomass market and trade in Norway: status and future prospects. Country report for IEA Task 40

Tveite B, Braastad H (2000) Tynning i granbestand. Effekten på tilvekst, dimensjonsfordeling og økonomi (Thinning in spruce stands. Effect on growth, dimensions and economy). Norwegian Forest Research Institute report 4/2000

US EPA (2006) Solid waste management and greenhouse gases: a life cycle assessment of emissions and sinks. U.S. Environmental Protection Agency report

Vadla K (2011) Stammekvisting som kvalitetsforbedrende tiltak (Pruning as quality improving method). http://www.skogoglandskap.no/fagartikler/2011/Stammekvisting. Accessed 1 November 2012

Vennesland B, Hohle AE, Kjøstelsen L, Gobakken LR (2013) Prosjektrapport Klimatre. Energiforbruk og kostnader - skog og bioenergi. (Project report Klimatre. Energy use and costs—forest and bioenergy.) Norwegian Forest and Landscape Institute report 14/13

Whittaker C, Mortimer N, Murphy R, Matthews R (2011) Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass Bioenerg 35(11):29–45

Ximenes FA, Grant T (2013) Quantifying the greenhouse benefits of the use of wood products in two popular house design in Sydney, Australia. Int J Life Cycle Assess 18:891–908